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14. ABSTRACT This was a DURIP project to acquire a suite of inverted echo sounders (IESs) equipped with pressure and current sensors (CPIESs). CPIESs are moored instruments that measure the round-trip acoustic travel time between the seafloor and the sea surface; bottom pressure and temperature; and near-bottom horizontal currents hourly for up to 5 years. Using an array of CPIESs—particularly when leveraged with other remote sensing and in situ observations—allows for investigations of ocean physics at a range of spatial and temporal scales. The goals of this project were to enhance the pool of pressure-sensor equipped IESs available at the Woods Hole Oceanographic Institution (WHOI); to foster partnerships between WHOI, other US groups, and international collaborators; to promote data analysis methods that combine CPIESs measurements with other in situ and remote sensing observations; and to promote developments of the CPIESs and related technologies. CPIESs obtained through this program are presently deployed in the equatorial North Pacific as part of the Flow Encountering Abrupt Topography (FLEAT) Department Research Initiative (DRI).					
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Variability at Multiple Scales: Using an Array of Current- and Pressure-Sensor Equipped Inverted Echo Sounders to Measure the Ocean

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Equipment List

- 4 Current and Pressure Sensor Equipped Inverted Echo Sounders (CPIES)
- 4 Aanderaa Current Sensor Heads (4930 Z-pulse)
- 1 Doppler Current Profiler Sensor (DCPS)—PIES
- 4 Popup Data Shuttles (PDS)

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1. Long Term Goals

This was a project under the Defense University Research Instrumentation Program (DURIP) to acquire a suite of inverted echo sounders (IESs) equipped with pressure and current sensors (CPIESs). CPIESs (**Figure 1**) are moored instruments that measure (1) the round-trip acoustic travel time between the seafloor and the sea surface, (2) bottom pressure and temperature, and (3) near-bottom horizontal currents hourly for up to 5 years. Using an array of CPIESs—particularly when leveraged with other remote sensing and in situ observations—allows for investigations of ocean physics at a range of spatial and temporal scales.

The goals of this project were (1) to enhance the pool of pressure-sensor equipped IESs available at the Woods Hole Oceanographic Institution (WHOI), (2) to foster partnerships between WHOI, other US groups, and international collaborators, (3) to promote data analysis methods that combine CPIESs measurements with other in situ and remote sensing observations and (4) to promote developments of the CPIESs and related technologies.



Figure 1. PIES schematic (left), a PIES on deck, ready for deployment (middle), and awaiting retrieval from the sea surface after a mission (right). The CPIES's current sensor (not shown here) is tethered above this PIES platform by a 50 m cable.

2. Objectives

The primary aim of this project was to contribute equipment to ongoing and future ONR-sponsored field work in support of those programs' objectives. A further objective of this project was to enable training of WHOI personnel and personnel from collaborating institutions on the preparation, deployment and refurbishment of CPIESs and to foster continued development of the CPIESs and related hardware.

Anticipated applications for the CPIESs obtained through this project included investigations of:

- (1) Low-frequency changes in Kuroshio strength, vertical structure and heat transport and the Kuroshio's potential role in the marked increase in SST observed on the East China Sea shelf.
- (2) Interactions of mesoscale eddies, internal waves and the Kuroshio east of Taiwan.
- (3) Interactions of large-scale flow with ocean ridges to generate westward-propagating baroclinic Rossby waves that emanate from ridges.

3. Approach

PIESs and CPIESs have been used in many field programs with widely varying applications. These include (1) process studies to examine the strength and variability of western boundary current absolute transports and velocity structure (e.g., Andres et al., 2016 submitted; Mensah et al., 2016; Andres et al., 2008; Donohue et al., 2010); (2) measurement of non-linear internal waves in the South China Sea (Li et al., 2009; Farmer et al., 2009); (3) contributions to the long-term monitoring efforts to observe variability the Atlantic meridional overturning circulation (e.g., in the RAPIC/MOCHA array along 24°N, see Meinen and Garzoli, 2014, and in the MOVE array at 16°N, see Kanzow et al., 2008); (4) measurement of ocean heat content variability at high latitudes (Straneo et al., manuscript in preparation) and (5) data interpretation methods for regions with icebergs and sea ice (Andres et al., 2015; FitzMaurice et al., 2016). While details of the IES/PIES/CPIES configurations depend on the specific science application, a general description of the CPIES instrument and data collected is given below.

3.1 CPIES technology

Each CPIES provides in situ time series measurements of surface-to-bottom round-trip acoustic-travel time (τ), bottom pressure and temperature, and near-bottom horizontal currents. Electronics and sensors (except for the current sensor) are housed in a glass sphere (**Figure 2**) surrounded by a protective hard hat. The CPIES is designed to sit on the seafloor in a rigid anchor stand in water depths D ranging between 500 and 6700 m. The current sensor is tethered to the glass sphere housing the IES electronics with a 50 m cable and is held upright by a float (so that the sensor is outside of the benthic boundary layer). The CPIES is launched from a ship for deployment periods lasting from less than one month to several years.

A CPIES's acoustic transducer emits 12 kHz pings and listens for each ping's first echo. In typical applications, twenty-four pings are emitted each hour in bursts of 4 at ten-minute interval with 6 ms ping duration and spacing alternating between 16 s and 18 s to avoid aliasing by surface swell. After a burst of four pings, the CPIES records only the travel-time of the first four echoes that



Figure 2. The internal CPIES electronics (front) and protective housing (rear).

fall above a minimum intensity threshold. Only strong reflectors are detected (e.g., the air-sea interface is detected, whereas the pycnocline within the water column is not). Subsurface echoes that arrive from strong reflectors – like nearby bottom topography or the current sensor or float in the water column directly above the IES – can be excluded with a user controlled lockout-time to maximize the number of echoes that sample the air-sea interface. Usually (though not in all applications), a CPIES is configured by the user with a lockout-time that is slightly shorter than the expected round-trip surface-to-bottom travel-time for the given water depth.

In addition to the 24 acoustic-travel-times measured each hour, a CPIES records bottom pressure, P_b , every hour measured with a Paroscientific Digiquartz pressure sensor. Temperature inside the glass housing, T_b , is also measured each hour. T_b is typically only used for the calibrations of the pressure sensor, rather than as an independent measure of ocean bottom temperature (although in some applications T_b has been calibrated with a Microcat and used for science purposes, e.g., Straneo et al., manuscript in preparation). The current sensor (an Aanderaa 4930 Z-pulse Doppler current sensor) measures horizontal current speed and direction as well as temperature hourly. The 50 m tether between the sensor and the IES allows for communications via a RS-232 communications port in the glass sphere that houses the IES; the IES provides the power and records the current sensor's hourly records. (A CPIES can also be deployed without the current sensor to operate as a PIES.)

CPIESs can also be equipped with a new technology, an optional 'PopLink transmitter' housed in the IES. Several expendable popup data shuttle (PDS) modules can be deployed with each PopLink-equipped CPIES. Data are broadcast hourly to all PDS modules. On an individually programmed schedule, each PDS will self-release and float to the surface. The data in the PDS memory will be transmitted via the Iridium gateway to an email server ashore. The PDS module provides a reliable and cost effective tool to retrieve data from a deployed CPIES without sending a ship.

3.2 Data interpretation

Since the speed of sound in seawater, c , is set by the water's temperature, salinity, and pressure (Del Grosso, 1974), the round-trip acoustic-travel-time (τ) between the IES and the overlying sea surface is a function of the water column's vertical salinity and temperature profiles. In many regions τ is uniquely related to the depth of the thermocline, D_T (Rossby, 1969), and to integrated quantities like the water column's heat content. In the strong western boundary currents, like the Gulf Stream or Kuroshio, and their extensions it is not only D_T and heat content, but the whole vertical structure which is strongly correlated with τ (e.g., Watts and Rossby, 1977; Meinen, 2001). In these strong western boundary currents, τ (measured with IESs, PIESs or CPIESs) has been used to infer full-water column density profiles ($\delta\rho/\delta z$), and horizontal gradients in τ have been used to infer velocity-shear using the thermal wind equation.

4. Tasks Completed

Over the course of this DURIP project, the CPIESs have been acquired, WHOI personnel and collaborating personnel have been trained, and CPIESs have been deployed in the field in support of the Office of Naval Research's (ONR's) Flow Encountering Abrupt Topography (FLEAT) DRI program. In addition, the CPIESs' supporting hardware has been improved

through an informal collaboration between WHOI, the University of Rhode Island (where the CPIESs are developed and manufactured), and Edgetech, a commercial supplier of deckboxes used for communications with oceanographic equipment. Tasks are described in further detail below.

4.1 CPIES Array north of Palau

Four CPIESs arrived at WHOI in March of 2016. With expansion of its in-house CPIESs capabilities, WHOI was able to provide these CPIESs and WHOI technical support as a contribution to the FLEAT DRI. Upon arrival at WHOI, the CPIESs were immediately shipped to Palau and were deployed north of Palau (**Figure 3**) from the R/V Revelle (cruise 1606, May 19-29 2016) by M. Andres and B. Hogue (WHOI) in an array coordinated with 5 additional PIESs (University of Rhode Island and Massachusetts Institute of Technology, T. Peacock) and 5 deep moorings and 3 shallow moorings (Naval Research Lab, H. Wijesekera). The full array will remain in place until April 2017.

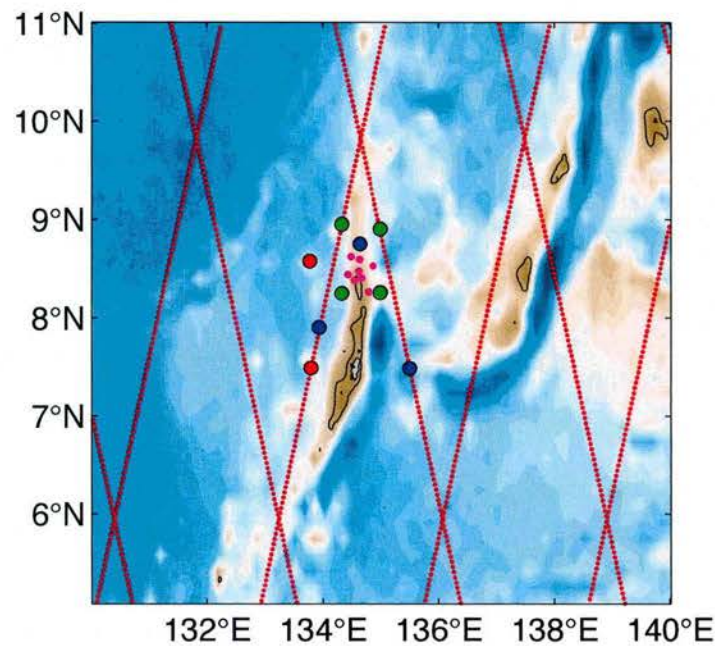


Figure 3. Moored instruments from the FLEAT array comprising: 4 CPIESs (green circles, WHOI/this project), which fall under repeated glider tracks (D. Rudnick) which run meridionally from Palau towards the north (tracks not shown); 3 PIESs (blue circles, University of Rhode Island/MIT, T. Peacock); 2 rapid-PIESs (red circles, University of Rhode Island/MIT, T. Peacock) and shallow moorings (magenta dots, NRL, H. Wijesekera). The red lines show the AVISO satellite tracks.

4.2 Technology developments

4.2.1 Deckbox

During the FLEAT deployment cruise in May 2016, a newly modified deckbox was field-tested. This was an Edgetech 8011M unit upgraded with the coding necessary to communicate with IESs (**Figure 4**). This is a newly developed capability on the 8011M; up to now, an older model

deckbox was generally required for PIES operations (either a Benthos DS7000 or an Edgetech 8011A). Since neither of these older models is currently in production, finding working units was becoming a significant challenge to the PIES-user community. The upgraded 8011M worked very well in the field and a few minor issues were identified (and have since been resolved by Edgetech). Further field testing was conducted by the PI this summer (in a separate project off Greenland) and now the PIES-communications capability is commercially available to the community.

Figure 4. Edgetech 8011M newly upgraded with URI codes for use with CPIES (choice 4 on the screen). See also: <http://www.edgetech.com/edgetech-news/ut-news/edgetech-8011m-acoustic-release-deck-box-is-now-available-with-uri-pies-communication-interface/>.



4.2.2 Profiler-PIES

A final PIES instrument was ordered from the University of Rhode Island with a new technology in place of the current sensor. This unit has an Aanderaa Doppler current profiler sensor (DCPS) integrated into the PIES system (i.e., a ‘DCPS-PIES’ rather than a ‘CPIES’). This system presents two advantages over a traditional CPIES: (1) there is no need for the 50-m communications cable linking the tethered current sensor to the rest of the PIES and (2) rather than providing the horizontal velocities at just 1 location—50 m above the bottom—the DCPS sensor provides the profile of horizontal velocities in bins from the bottom to about 80 m above the bottom. This instrument is not deployed as part of the FLEAT array, the PI is presently exploring collaborations so this instrument can be used in support of ONR programs.

4.2.3 Data Pods

While the CPIES acquired through this DURIP were built with the internal PopLink capability, no PDS modules have been used in the field yet since the first application for these CPIESs (see section 4.1) is a relatively short duration (< 1 year) field program. It is anticipated that the PopLink technology will be used in the future deployments of these CPIESs.

4.3 Best practices for leveraging PIES observations

Recent work east of Luzon and Taiwan has shown that PIESs can be leveraged with observations from gliders, upward-looking acoustic Doppler current profilers (ADCPs, **Figure 5**) and satellite altimetry (**Figure 6**) to characterize variability in the meso-scale flow and investigate the underlying dynamics. Results have been carefully evaluated (Mensah et al., 2016) and used to explore the interactions between the Kuroshio and meso-scale eddies and the role of topography in controlling the flow there (Andres et al., 2016). These

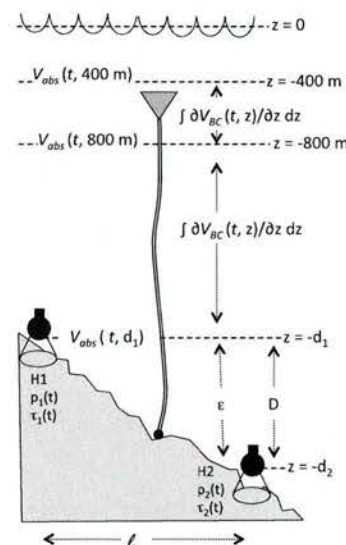


Figure 5. Schematic of the leveling procedure that uses an upward-looking ADCP to level the neighboring PIESs (H1 and H2); from figure 5 of Mensah et al., 2016.

results motivated the FLEAT C/PIES-array design and the methods will be used to help integrate the FLEAT C/PIES observations with the rest of the FLEAT observational and modeling efforts.

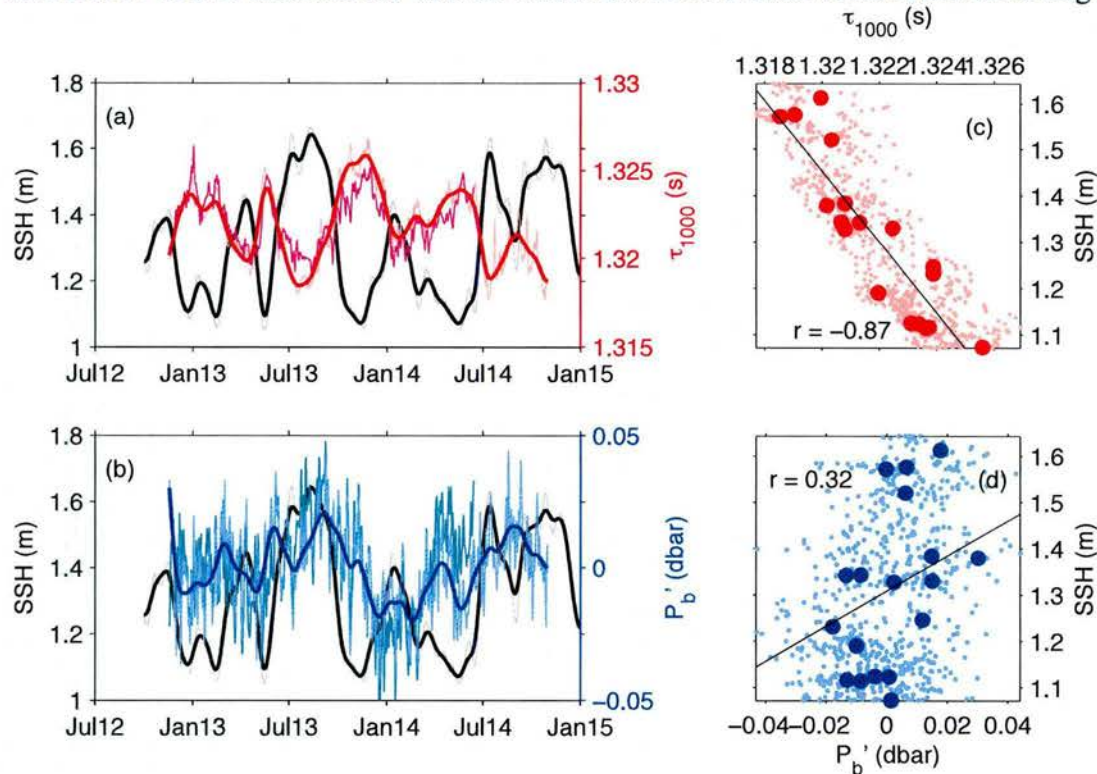


Figure 6. Example of PIES data leveraged with satellite altimetry from instruments deployed east of Taiwan; the same types of analyses will be performed with the DURIP C/PIESs which are presently in the water near Palau through the FLEAT DRI. Panel (a): comparison of SSH and acoustic travel time records showing time series of the SSH (at 123°E, 23.375°N from the Aviso mapped absolute dynamic topography) daily product (gray) and with a 40-day low-pass filter applied (black). Also plotted is the time series of the 3-day low-pass filtered τ_{1000} from T-P5 (light red) with a 40-day filter applied (red); the shorter τ_{1000} record from T-P4 is shown for comparison (magenta). Panel (b): comparison of SSH (as in a) with bottom pressure records showing the 3-day low-pass filtered P_b' from T-P5 (light blue) and with a 40-day low-pass filter applied (heavy blue). The P_b' record from T-P4 is shown for comparison (cyan). Panel (c) shows the negative correlation at T-P5 of SSH with τ_{1000} for the total signals (light red dots) and the 40-day low-pass filtered records (heavy red dots, plotted for every 40th day). Panel (d) shows the positive correlation at T-P5 of SSH with P_b' for the total signals (light blue dots) and the 40-day lowpass filtered records (heavy blue dots, plotted for every 40th day). Figure from Andres et al., submitted.

4.4 Training and workforce development

Through this project, two WHOI technicians (B. Hogue and A. Davies) were trained in PIESs instrument refurbishments, together with three visiting collaborators from National Taiwan University (S.-C. Shie, B. Wang, N. Taniguchi). The training was part of a workshop held at WHOI in January 2016, led by an engineer from the University of Rhode Island. Additionally, B. Hogue took part in C/PIESs deployment training at the University of Rhode Island; the

CPIESs funded through this proposal were used for the hands-on component of that training class. During the FLEAT deployment cruise in May 2016, a postdoc from MIT, R. Musgrave, was trained in C/PIES operations. The data from the WHOI, URI and MIT C/PIES will contribute to her postdoc research project.

5. Results

The CPIES obtained through this DURIP are contributing significantly to the overall in situ FLEAT array. The locations of the 4 CPIESs and 5 PIESs (with the latter provided by T. Peacock's program) has significantly helped the enhance the capabilities of the array:

- (1) The array will provide **information about the mesoscale** flow—at better temporal and spatial resolution than can be provided by altimetry—to establish the boundary conditions for the area sampled by H. Wijesekera's moorings (magenta dots in [Figure 3](#)).
- (2) The array will allow us to **decompose SSH into baroclinic (steric) and barotropic (mass loading)** components to explore upper/deep ocean coupling and the role of topography

The sites chosen for the C/PIES locations were motivated with four outcomes in mind:

- Mapping: we expect the scale of the topography matters more in setting the correlation length scales than does the region's deformation radius.
- Role of the ridge: we expect enhanced baroclinic variability west of the ridge that extends northward from Palau based on output from an idealized numerical model ([Figure 7](#) and Andres et al., 2012). We will test this by comparing the C/PIESs' pressure, bottom currents, τ and SSH collected on either side of the ridge.
- Barotropic variability: we expect strong bottom pressure variance east of Palau and strong τ variability west of Palau based on the results of output from a high resolution numerical model ([Figure 8](#)).
- Searching for non-linear internal waves: based on results from a numerical model ([Figure 9](#)), we expect to see evidence of non-linear internal waves with the Rapid-PIES propagating from the northwest (possibly generated at the Luzon St.) and southwest (possibly generated at the Sangihe Is.).

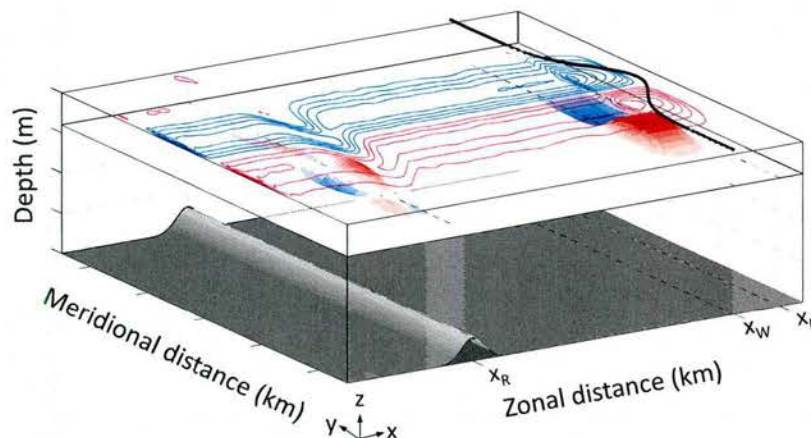


Figure 7. Output from an idealized numerical model (Andres et al., 2012) showing the generation of baroclinic variability west of a ridge.

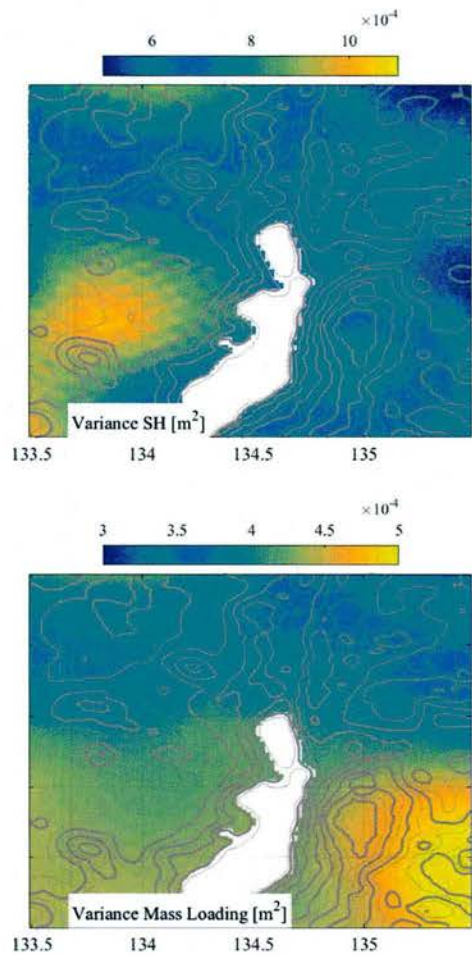


Figure 8. Results from a high resolution numerical model indicating high barotropic variance east of Palau (yellow shading in the lower panel) and high variance in steric height west of Palau (yellow shading in the upper panel). Figure courtesy of R. Musgrave.

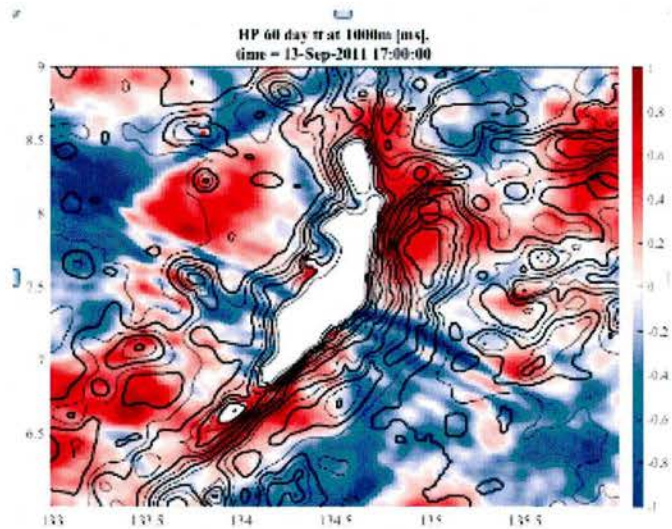


Figure 9. Output from a numerical model that suggests Palau is inundated by non linear internal waves. Wave fronts can be seen arriving from the northwest and southwest. Figure courtesy of R. Musgrave

6. Impact for Science

This project is impacting science by promoting best practices for leveraging CPIESs with other instruments and by spurring technological enhancements to the CPIESs. CPIES capabilities and potential applications for the FLEAT DRI were presented at a PI meeting (21-22 January, 2016 in La Jolla, CA) and the science goals of the deployed array were presented at a second PI meeting (6-7 October, 2016 in Seattle, WA). Results from the FLEAT deployment cruise have been disseminated in a cruise report. Results from the deckbox upgrades are being communicated informally to the PIES-users network, including international collaborators, and a via short user's guide written by the WHOI technical staff. Once the CPIESs are recovered (expected to be April 2017), they will contribute to science results to published in peer reviewed journals.

7. Relationship to Other Programs

The CPIESs acquired through this DURIP are presently being used in the field around Palau to complement several other components of the in situ array deployed through ONR's Flow Encountering Abrupt Topography (FLEAT) DRI. It is anticipated that the CPIESs will be recovered in April 2017. A subset of these instruments may be refurbished quickly and used in the field in the western Pacific (Philippine Sea or East China Sea) to complement ongoing ONR collaborations with our Taiwanese colleagues whose Study of the Kuroshio-II (SK-II) program (**Figure 10**) is being funded by the Taiwan Ministry of Science and Technology (MOST). This effort builds on the results from two companion field programs—Origins of the Kuroshio and Mindanao Currents (OKMC) funded by ONR and Observations of Kuroshio Transport Variability (OKTV) funded by MOST (**Figure 11**) and ONR's earlier Quantifying and Exploring Uncertainty (QPE) program in the East China Sea (Gawarkiewicz et al., 2011).

A planning letter was also submitted to the Inner Shelf DRI ('Off-Shelf Measurements of Locally and Remotely Generated Internal Tides', M. Buijsman, M. Andres, B. Arbic, J. Shriver, J. Richman) to use the CPIESs to study internal tide east of California near Pt. Sal. While this effort is not being funded through the Inner Shelf DRI, we anticipate that the CPIESs may be used in the future to help validate the predictability of remotely generated internal tides as represented in HYCOM.

Figure 11. The OKMC/OKTV array east of Taiwan with ADCPs (red triangles), PIESs (yellow circles) and a CPIES (PIES with an additional current sensor, green circle) and the companion OKMC project east of Luzon with ADCPs (red triangles) and HPIES (PIES with an HEF sensor, orange circles). Blue lines indicate satellite tracks.

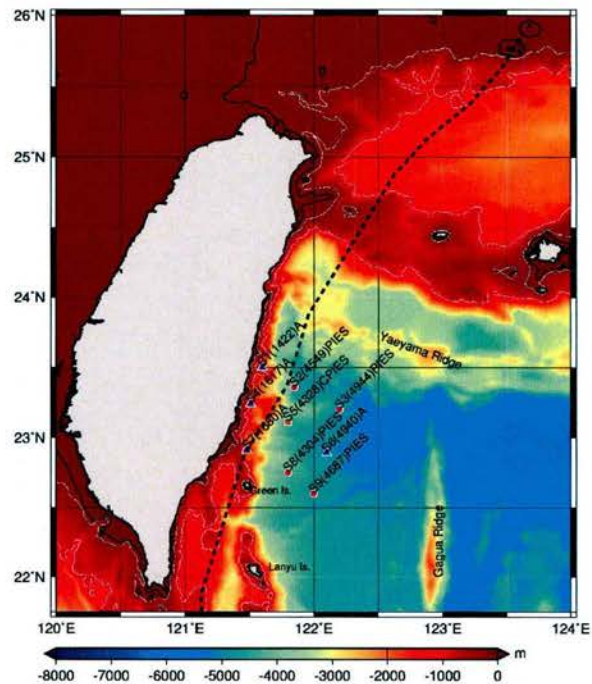
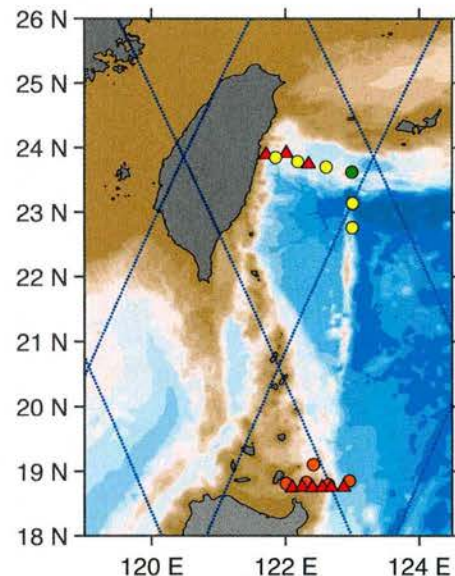


Figure 10. Recently deployed SK-II array, motivated in part by the findings from this study. These moorings will remain in the water from ~12 months and were deployed April 2016.



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